The Development of a Magnetically Enhanced Hydrogen Gas Dissociator

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Application of a dc magnetic field on an rf hydrogen gas dissociator has led to the development of a more efficient source of atoms for hydrogen masers. We discuss the influence of the applied magnetic field on the plasma and some details of the resulting enhancement of the dissociation efficiency. We also consider the ways that this improved efficiency can result in the enhancement of the operation and field life of hydrogen masers, as well as aid the development of spaceborne masers.

I. Introduction

The development of an rf hydrogen gas dissociator, efficient in both atom production and power consumption, is of great interest in hydrogen maser research and development. The significance of a low-powered source for spaceborne masers is self evident: it reduces the power requirement for the operation of the maser and aids the power economy in the spacecraft. In ground-based masers, an efficient source can contribute to a more reliable operation as well as extended operational life.

The details of the influence of the rf dissociator on the operation of the hydrogen maser have been previously discussed (Ref. 1). Briefly, the dissociator produces atoms that, upon their exit through a multichannel collimator, form an atomic beam of hydrogen. The beam enters the inhomogeneous field of a state selecting magnet which focuses atoms in a particular hyperfine sublevel into the entrance of a storage bulb within the maser high-Q cavity. The stored atoms interact with the microwave field coupled to the cavity, and undergo stimulated emission.

The efficiency of the dissociator in atom production can then affect the operation of the maser in three important ways. First, since the state selecting magnet cannot alter the path of undissociated molecules which exit the collimator, a significant number may enter the storage bulb in the cavity. The presence of the molecules in the storage bulb, the number of which depends on dissociation efficiency, contributes to collisional line broadening of the hydrogen line. Second, the required back pressure of the hydrogen gas for production of a useful flux of atoms, as determined by the source efficiency, constitutes the load on the vacuum pumps. The vacuum pump saturation and the resulting decrease in their hydrogen capacity is a frequently encountered mode of maser failure. Finally, parameters of pressure and input power directly influence the operational life of the dissociator itself. The failure of the hydrogen gas dissociator is also an often encountered mode of maser failure.

Motivated by the above consideration, we undertook to improve the operational efficiency of the rf hydrogen gas dissociator (source), based on an initial study of the rf plasma processes (Ref. 1). Here we report on the development of an rf hydrogen source which is capable of producing atoms with an efficiency comparable to conventional sources, but which consumes a significantly lower input rf power. This source can also operate in a low pressure mode, where the efficiency in atom production is improved, while the power is kept constant. The improvement in the source performance is obtained by the application of a dc magnetic field on a conventional rf dissociator.

In Section II of this paper we discuss theoretical background and the relevant concepts for this atom source. Section III presents some details of the source and its operation. Finally, a summary is given in Section IV, together with an outline of recommended future work.

II. Theory

Molecular dissociation in an rf plasma is due to the collision of molecules with electrons that move under the influence of the applied rf field. The rf field is coupled to the source in a capacitive or an inductive mode. In inductively coupled schemes, as employed in JPL masers, the motion of electrons may be regarded as circular motion about the axis of the oscillating magnetic field. These electrons transfer their energy to particles in the plasma through inelastic collisions and are eventually lost to the walls of the source or to recombination processes with positive ions. The efficiency of atom production in the rf source is therefore related to the energy of the electrons, as well as their collisional frequency with hydrogen molecules. The energy of the electrons is determined by the power input, while their collision frequency is related to molecular density via the pressure in the source. It is, however, undesirable to increase the power input or the source pressure in order to improve the efficiency of the atom production. An increase in the power, which is undesirable for spaceborne maser application, is responsible for generation of ions with higher energies. As the energetic ions collide with the glass wall, they cause sputtering, which then results in an increase in the recombination rate of hydrogen atoms on the walls. With a gradual degradation of the glass walls, the operational life of the source is degraded accordingly. As for the increase in the number density of molecules by increasing the pressure, we have already mentioned the desirability of a reduced gas load to the vacuum pumps, as well as a reduced molecular density in the storage bulb.

Consider, however, the motion of an electron in an rf plasma which is superimposed by an axial dc magnetic field. The electron will experience a force $\mathbf{F} = e\mathbf{v} \times \mathbf{B}$, where $\mathbf{v}$ is the electron velocity and $\mathbf{B}$ is the magnetic induction. This implies that the path of electrons would be modified through the action of the field on the component of velocity perpendicular to it. The result is that the electron will circulate the field with Larmor frequency $f = eH/2\pi mc$, while its parallel motion is unaffected by the field. Here H is the magnetic field, m is the mass of the electron, and c the velocity of light. The helical motion of the electron thus modified constitutes a lengthening of its path in the plasma, as compared to its path in the absence of the magnetic field. Furthermore, the circulating electron in the dc field can now absorb energy in resonance from the field as it moves in the direction of the field, when its cyclotron frequency $\omega_c = eH/mc$ is equal to the frequency of the oscillating field ω.

In this manner, it is possible to increase the efficiency of atom production in the rf dissociator by the application of the magnetic field. It should be mentioned that dc magnetic fields have been previously applied to rf plasmas used for production of positive ions (Ref. 2). While small dc fields do not directly affect the path of ions due to ions' relatively large mass, they significantly modify the drift of ions in the plasma (Ref. 3). It is the modification of ion drift that primarily contributes to improved performance of rf ion sources with axial dc magnetic fields. Furthermore, because of the general dependence of the ionization cross-section on energy (Ref. 4), increased electron energy due to the applied dc field directly improves ion production in rf ion sources, an effect that is not necessarily desirable in molecular dissociation. It is therefore quite important to keep in mind that the influence of a dc magnetic field on the efficiency of atom production in rf dissociators is significantly different from its influence on ion current production in rf ion sources.

III. The Source and Its Operation

Because the hydrogen gas dissociator assembly of JPL masers is inside the vacuum package and therefore not accessible without breaking of vacuum, a dissociator test bed was constructed. The test bed consists of a vacuum canister for connecting an ion pump to a source mating flange. A pyrex glass bulb was designed and constructed with dimensions identical to those of conventional sources used in JPL masers, but suitably modified for use in the test bed. The modification consists of a glass ring with an O-ring groove externally attached to the wall of the source containing the exit collimating holes. The source may then be positioned on the flange with the O-ring providing the necessary vacuum seal. The rf exciter coil assembly and hydrogen gas feed lines provide the necessary support for the glass bulb. A picture of the test bed and the source is given in Fig. 1.

For the generation of the dc magnetic field a solenoid was constructed from an insulated copper wire wound on a copper cylinder with an inside diameter one inch larger than the diameter of the dissociator bulb. The solenoid was placed on the mating flange in a coaxial configuration with the source. This particular solenoid provided a maximum field of 145 gauss on its axis with a 2.0-A current input. The solenoid produced a field which was linearly dependent on current within the range of zero to 2.0-A, the maximum current which the power supply produced.

The dissociation efficiency of the source was determined by measuring the changes in the pressure observed when the plasma was on or off. The variation of the pressure was obtained by noting the current in the ion pump power supply. While this method of efficiency determination for the dissociation lacks a high absolute accuracy, it does provide a satisfactory means for a relative determination of the dissociator efficiency.

The source was initially operated under the condition of power and pressure similar to those employed in the maser. A back pressure of hydrogen gas produced a pressure of 200 m torr in the dissociator; an rf power input of 3 W produced an efficiency measured to be 5%. As the input power was decreased, the efficiency of the source deteriorated, and the plasma was not sustained if the power was reduced below 2 W. The source was left to operate under normal operating conditions for a period of a few days to allow its performance to stabilize. After this period, the solenoid power supply was turned on and the solenoid current was varied between zero and 2 A. As the magnetic field was increased, the light intensity of the plasma increased significantly. Furthermore, for specific values of the field a change in the plasma mode was observed. A measurement of the efficiency of the source at this level of pressure and power was performed with the dc magnet on. The source exhibited an increase and a decrease in efficiency depending on the magnitude of the applied magnetic field. The amount of variation in the efficiency ranged from a 10% increase to a 10% decrease of the efficiency measured without the applied magnetic field.

The efficiency measurements were continued as the input rf power was decreased. First it was observed that the application of the magnetic field decreased the value of the minimum power required for maintaining a plasma, depending on the current in the solenoid. For a current of 0.4 A corresponding to a field of approximately 40 gauss, it was possible to reduce the power to about 0.3 W. With these parameters, the efficiency of the source was determined to be 5%, the same value as the efficiency of a conventional source operating with 3 W of input rf power. The dc magnetic field then resulted in a tenfold decrease in the power consumption.

This result could be predicted in the following way. At a given value of pressure, a specific level of input power yields the optimum efficiency. A decrease in this power level would decrease the efficiency, while an increase in the level does not necessarily lead to increased efficiency because of the difference in the dissociation energy of the hydrogen molecule (4.8 eV) and its ionization potential (15.8 eV). While the dissociation and ionization of the molecule constitute competing processes in the rf plasma, an increase in the average energy of electrons, with a Maxwellian energy distribution in the plasma, contributes preferentially to the ionization process, rather than the desired dissociation of the molecules. Therefore increasing power from the optimal level may in fact decrease the dissociation efficiency by contributing to the ionization process, via the increase in the energy of electrons. Conversely, when the power is decreased from the optimum level, an appropriate magnetic field strength can enhance the dissociation by allowing the electrons circulating with cyclotron frequency to absorb energy in resonance with the field and regain the condition of optimal energy for maximum dissociation efficiency.

Based on this consideration, we decided to investigate the influence of an inhomogeneous field on the efficiency of the source. We reasoned that if the energetic electrons in the high energy tail of the Maxwellian distribution could be swept away from the region near the exit of the source, a larger number of electronic collisions with the molecules will result in dissociation in that region, rather than the competing ionization. A test of this reasoning was demonstrated by distorting the homogeneity of the magnetic field through positioning the axis of the solenoid away from the axis of the source. When the solenoid was positioned with its axis about 1/2 inch away from the source axis, an increase in the dissociation was observed for a 200-m torr pressure of hydrogen. With a decrease in the pressure to 80 m torr, the measured dissociation efficiency of the source increased from a 7% level to 12.8% when a current of 0.75 A was applied to the solenoid; this is a 70% increase of the dissociation efficiency. The power level in both cases was 2.5 W.

While the configuration of the inhomogeneous field was somewhat arbitrary, determined by the constraint of the existing setup, it clearly demonstrated the potential value of this approach in designing a highly efficient source. It should be mentioned, however, that such a design should include consideration of influence of the inhomogeneous magnetic field on the production of secondary electrons released by particle impact with the walls. These electrons participate in plasma processes and influence the parameters of the rf plasma.

IV. Summary and Conclusion

The development of a dc magnetic field to the rf dissociation has yielded the following results:

(1) For a specific value of the magnetic field, it is possible to maintain the efficiency of the source and yet decrease the rf power input by an order of magnitude. This conclusion is of significance to both spaceborne maser development and improved reliability of ground-based masers through the expected improvement in the source life.

(2) It is possible to obtain good efficiency for the source and, at the same time, reduce the hydrogen pressure with an applied dc magnetic field. This finding implies a means for the reduction of the gas load to the maser vacuum pumps, thereby increasing their operational life, and reducing the frequency of maser breakdowns resulting from pump failures.

(3) The results with the inhomogeneous field indicate that it is possible to design a magnetic field configuration to sweep energetic electrons away from the region near the source exit. This would increase the source efficiency by preferential dissociation of the molecules, as compared to the competing process of molecular ionization.

(4) The application of a magnetic field on the rf plasma results in a significant increase of the light output from the plasma. While this effect is not of interest to maser application (except for reaffirming that there is no direct relationship between the efficiency of the source and the intensity of the emitted plasma light) it may be of significance in other applications. In particular, certain light sources such as mercury ion light source, and rubidium light source, employ rf power for excitation. An application of a dc magnetic field can improve the performance of those sources and extend their operational life.

The investigation of the performance of the source was determined in a test bed and by obtaining the dissociation efficiency through the measurement of pressure variations. It is obvious that it would be highly desirable, and necessary, to perform the tests using a hydrogen maser. In this way, the extent of improvement obtained with the new source in relation to the maser vacuum system, power output, and line Q may be directly determined. Efforts are presently underway to design and construct a source unit which may be mounted externally to our existing maser test assembly. We intend to optimize the configuration and the strength of the magnetic field for a desirable mode of source and maser operation. Once this is accomplished, we will substitute equivalent permanent magnets for the solenoid, thereby eliminating the need for a solenoid power source. Finally, we intend to test the influence of the magnetic field on the light output of mercury lamps, which will be utilized in a trapped mercury ion frequency source. The results of this investigation will be reported in a later paper.

References

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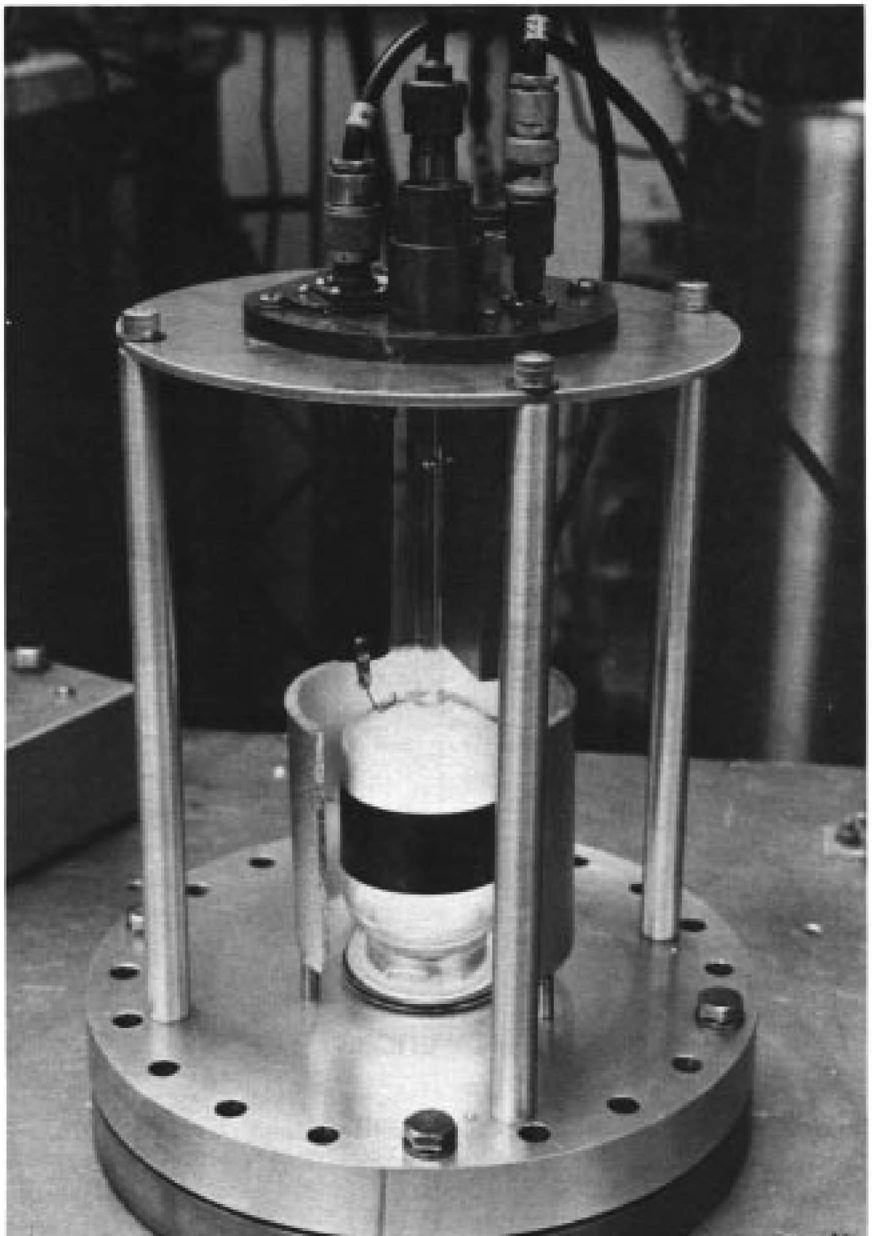

Fig. 1. Hydrogen gas dissociator installation on test bed